Discrete and continuum simulations of near-field ground motion from SPE

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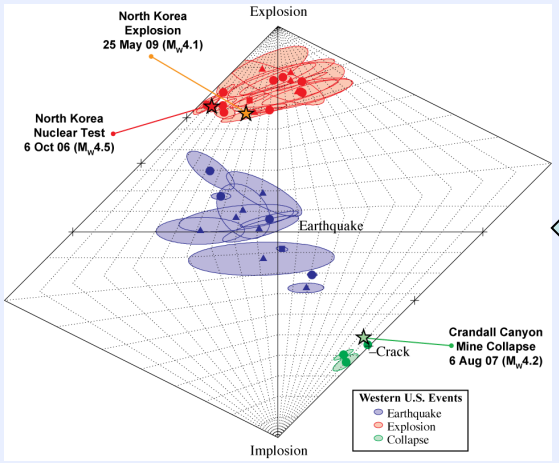
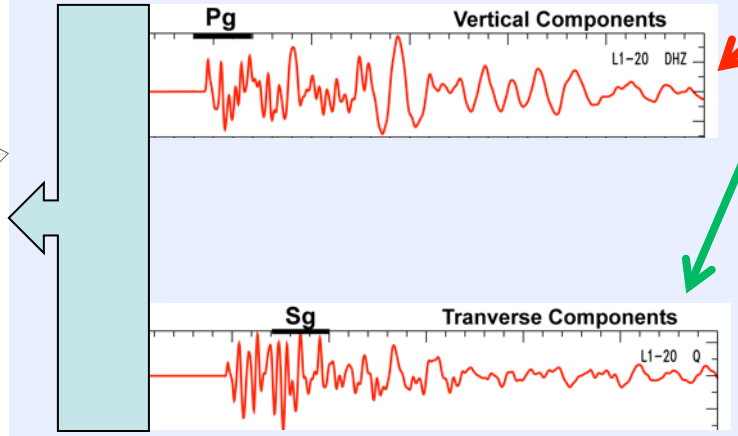
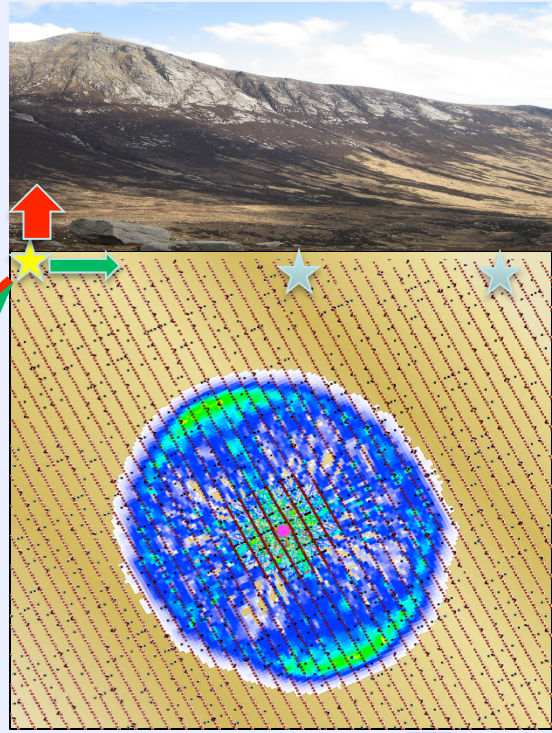
What can we learn from near field modeling ?

- ***Shear-wave generation, implications for monitoring***
- ***Role of site characterization***
- ***Role of surface and gravity***
- ***Scalability with yield***
- ***Source model for the far field***



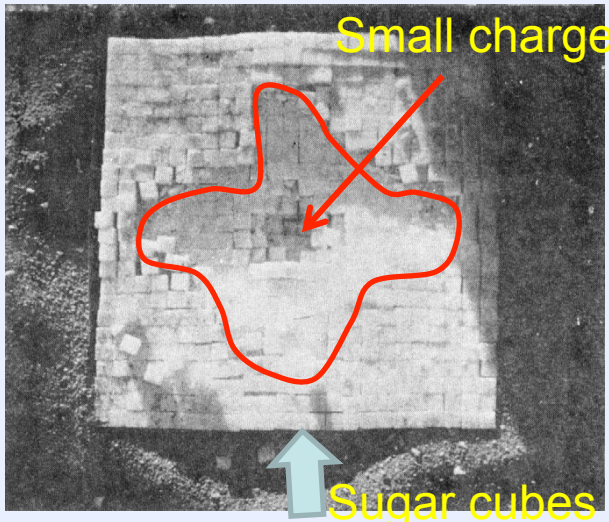




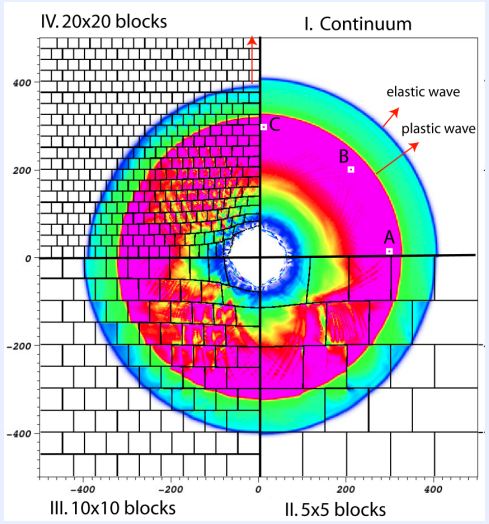
Joints can redirect energy flow from the source

Small scale experiment

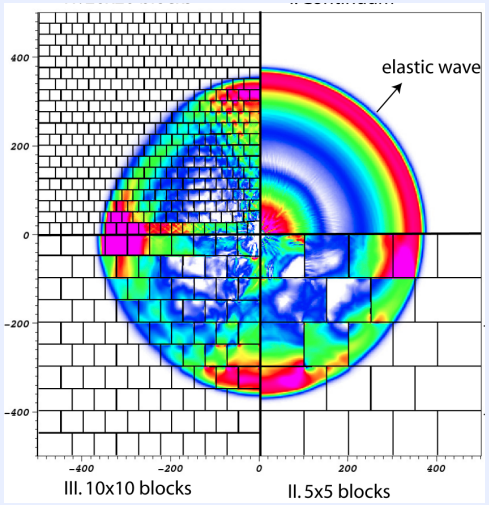
Sugar shot (Melzer, 1970)



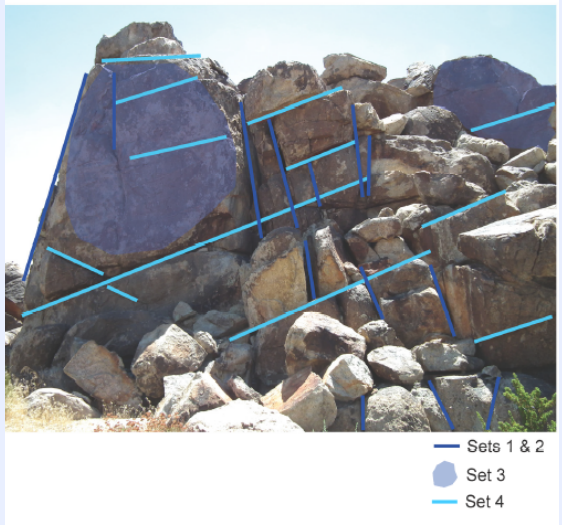
High confinement

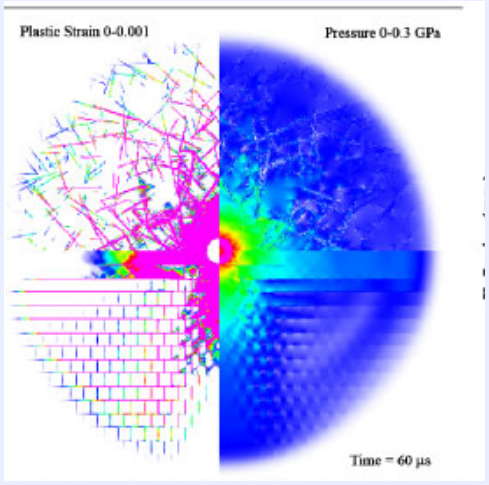


Low confinement



Joint sets at SPE site





Random joints

Vorobiev, IJNME, 2010

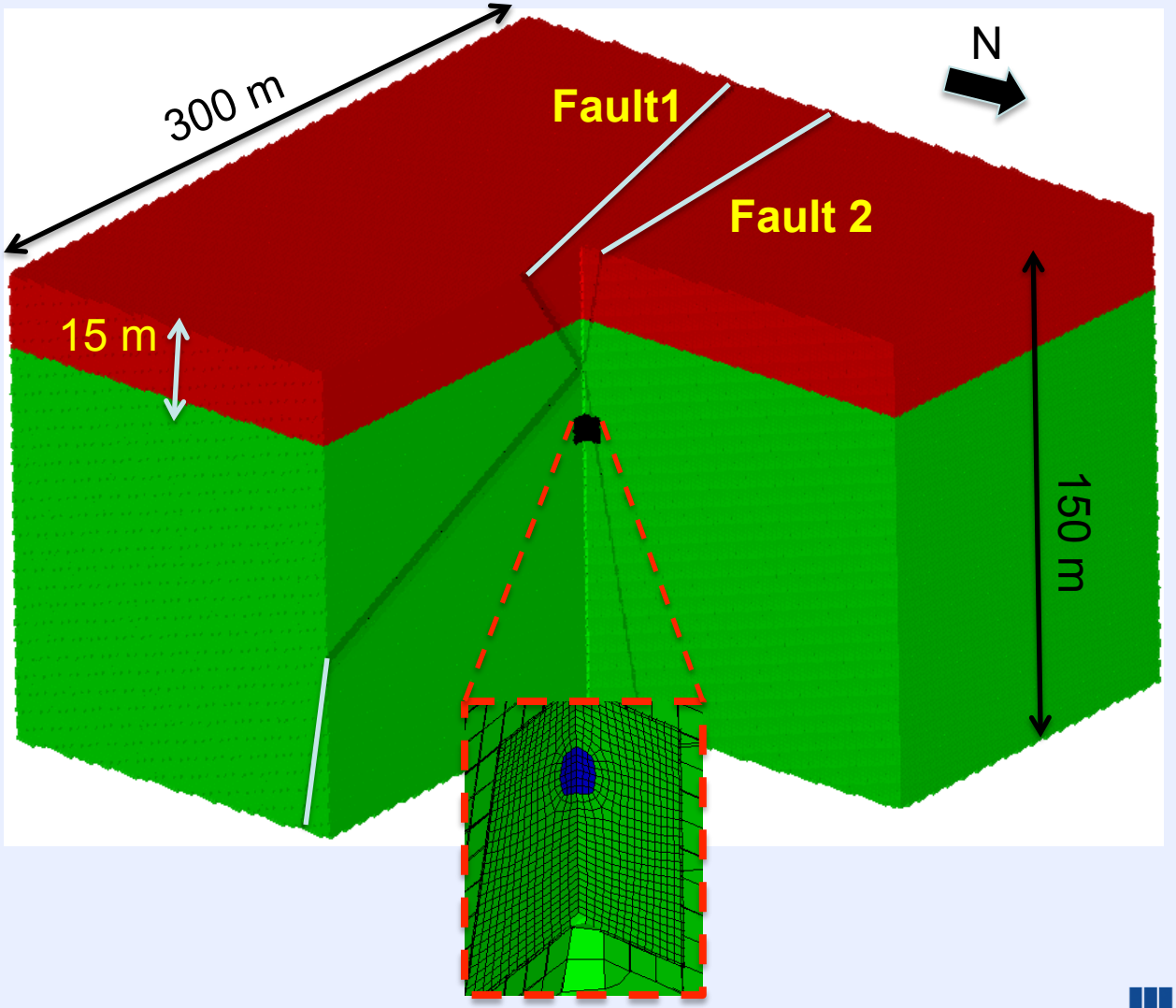
Parallel nonlinear code GEODYN-L is used to model near-source ground motion

Dimensions:

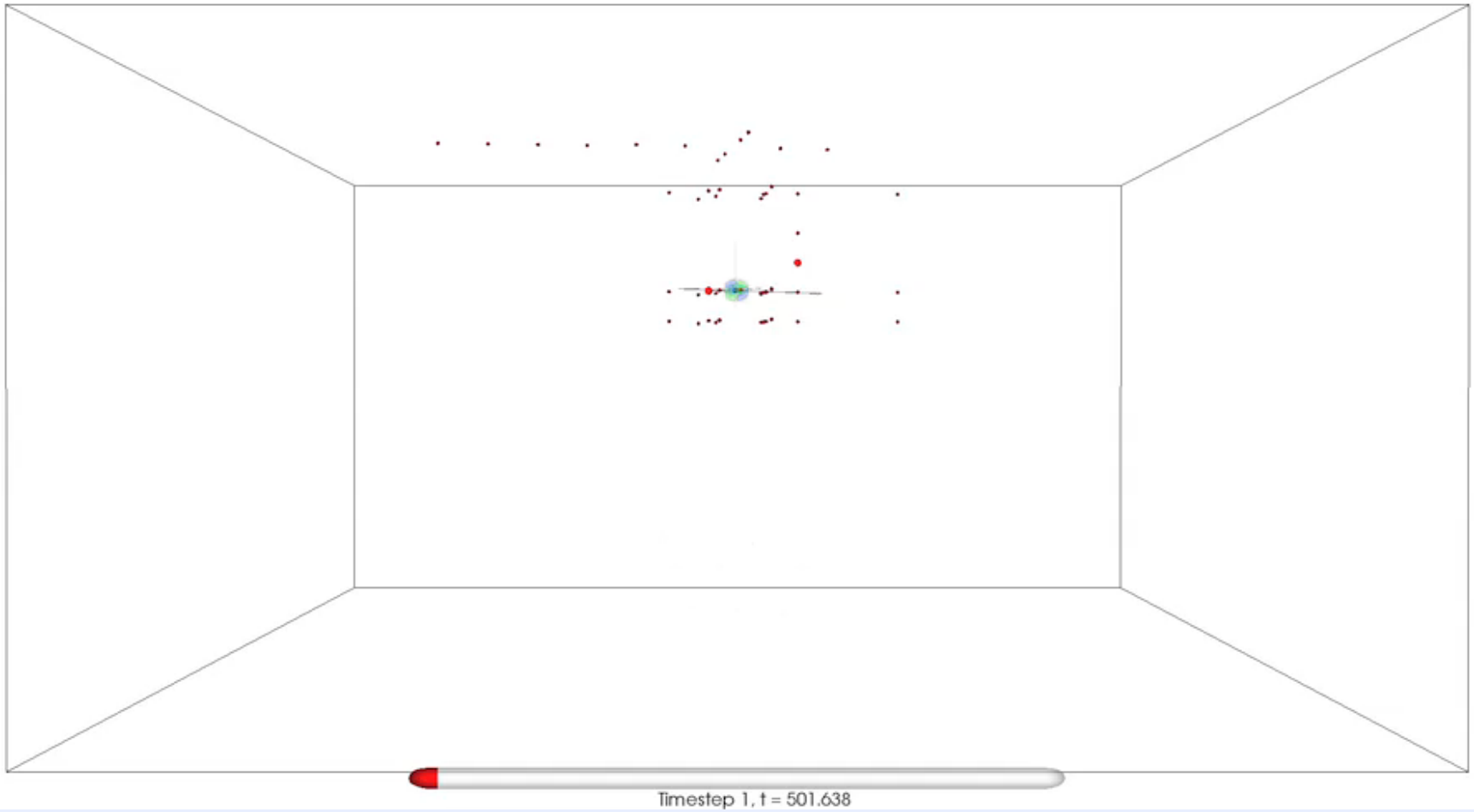
joint aperture ~1 mm
joints spacing ~ 1 m
source size ~1 m
region ~300 m

Computational model:

~20-50 million elements
~100-200 million zones
3240 CPU for 12 hours



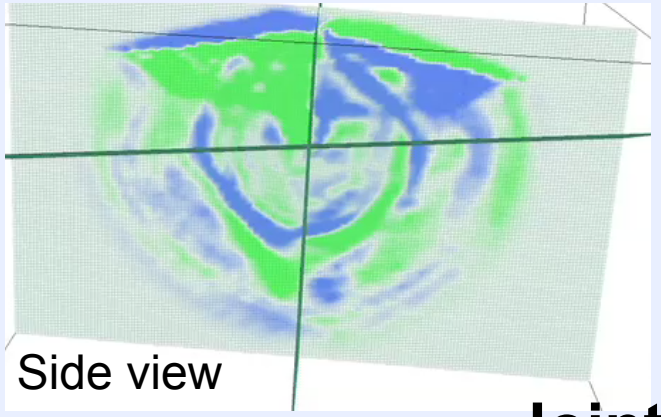
SPE3 discrete model: horizontal shear wave generation



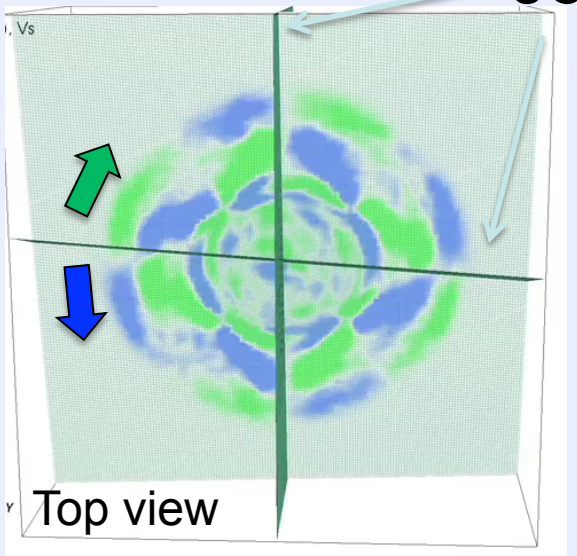
Discrete-continuum simulation of SPE3 using GEODYN-L

Vertical joint sets define polarity of horizontal shear motion

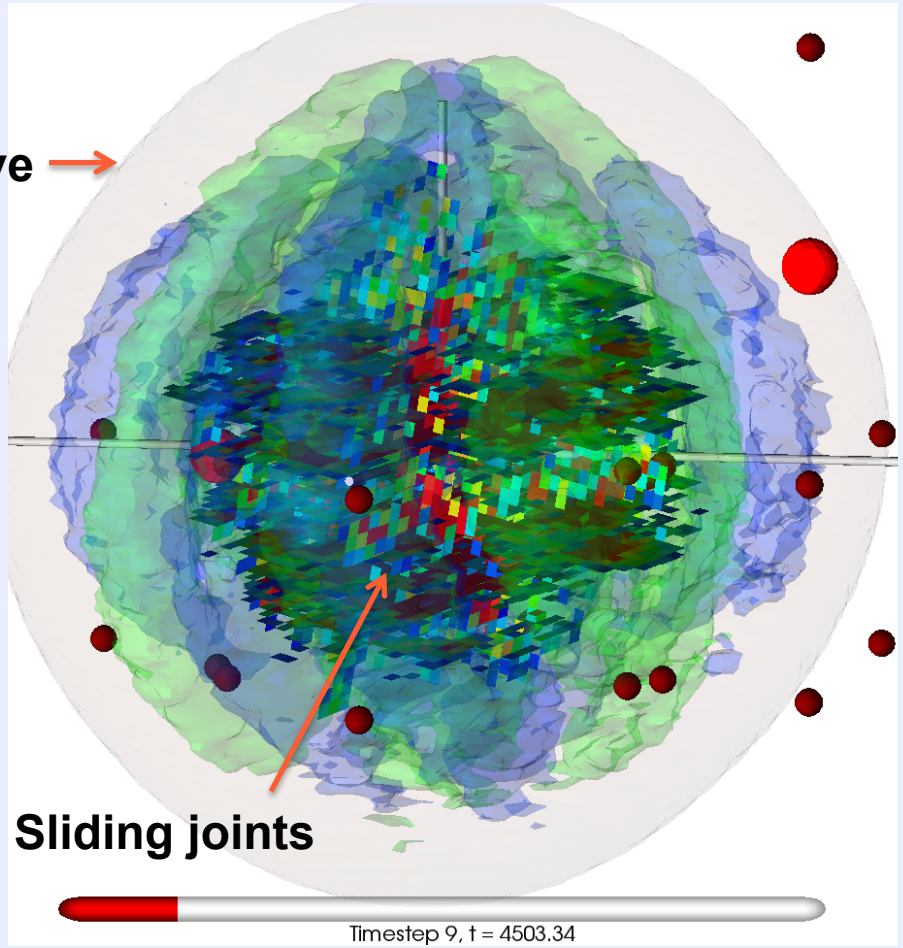
Horizontal shear motion of different polarity



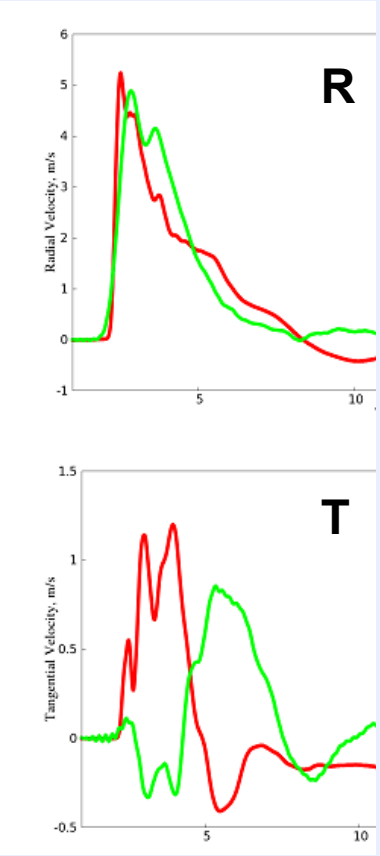
Joint planes



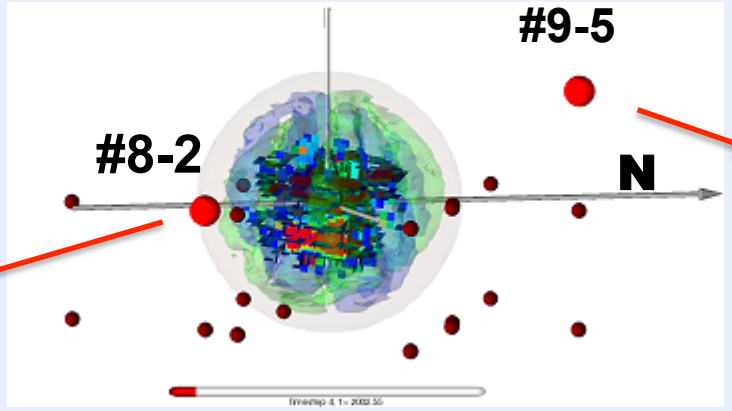
p-wave



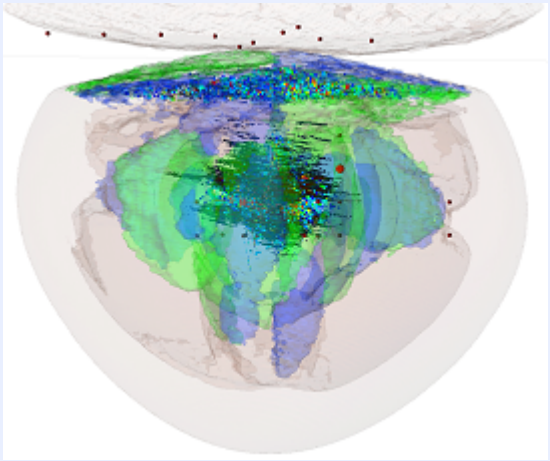
3D discrete model with 3 joint sets : sliding joints produce shear motion

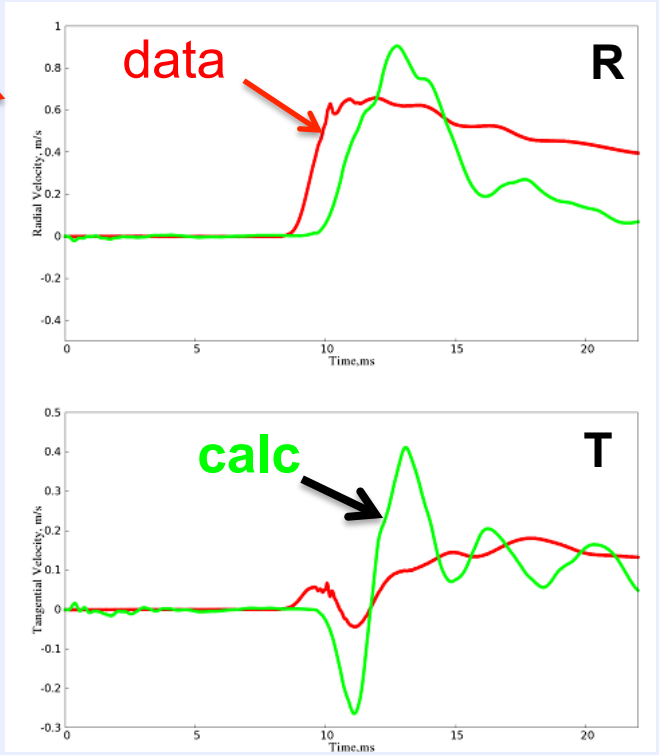


t=2 ms



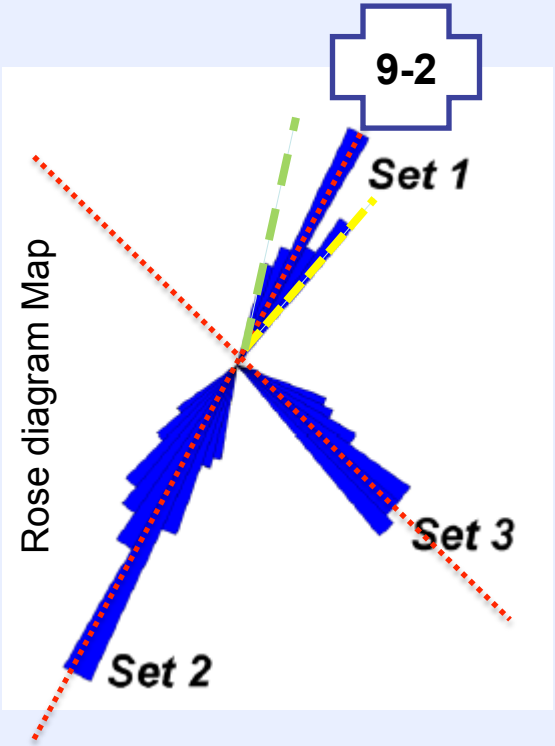
t=20 ms



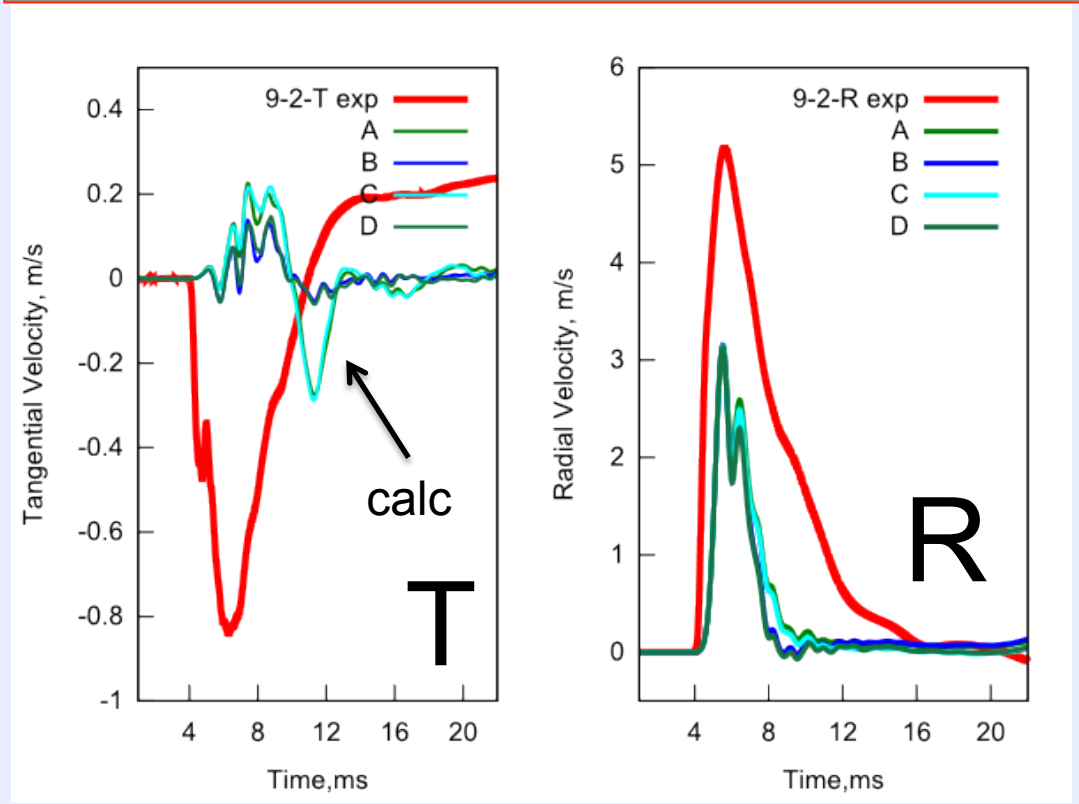


Two vertical joint sets used in calculations cannot explain observed shear motion

#9-2 *located at the source level in normal direction to vertical joint set 1 (which corresponds to high dip angle sets Set-1 and Set-2)*

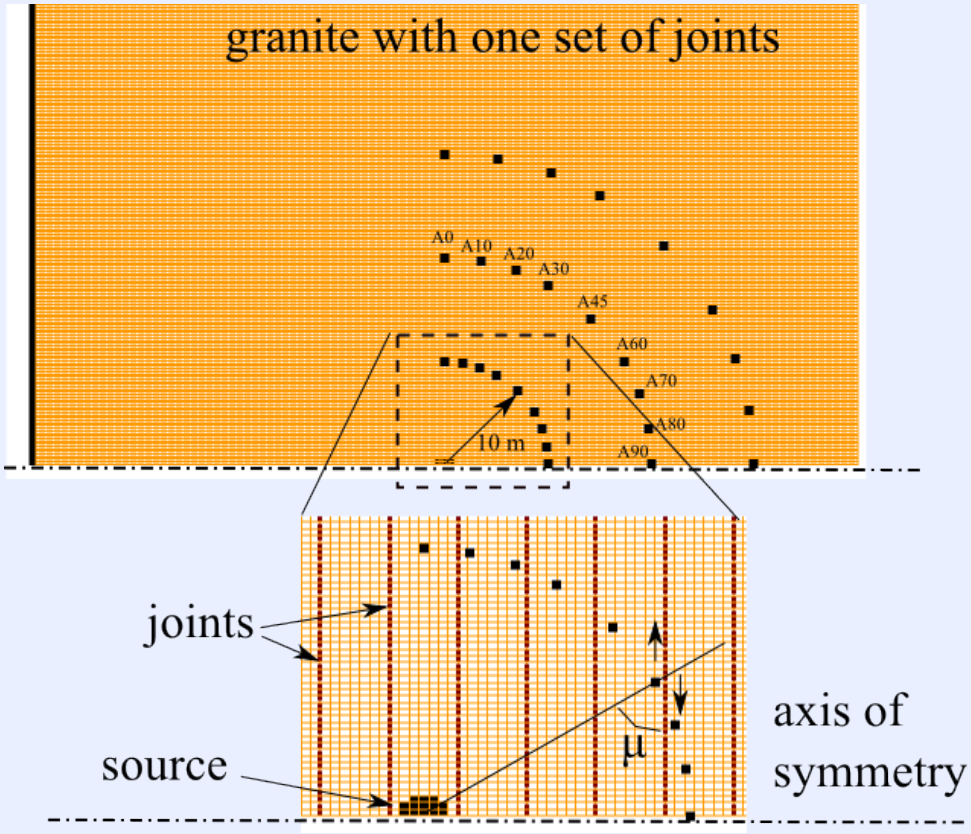


Data vs calculations at 20 m Range

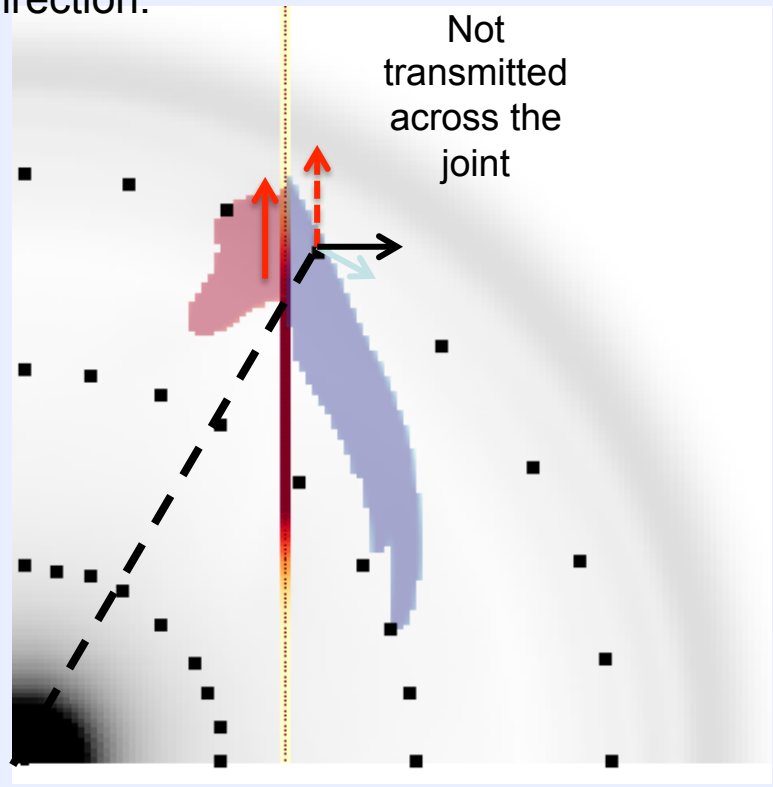


A single vertical joint generates shear motion but not over sufficiently wide azimuth

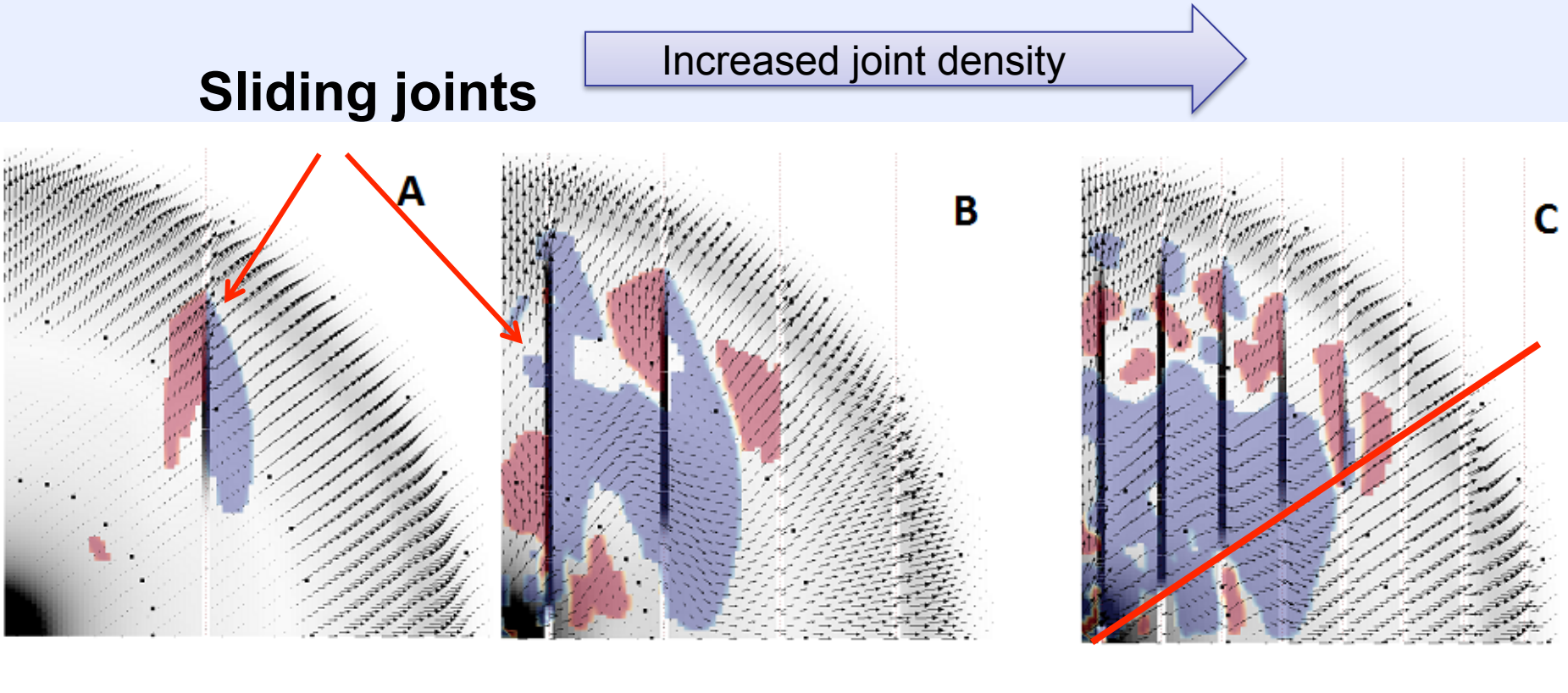
2D: Motion at 10 and 20 m range for locations oriented at various angles relative to the joint direction:
Joints slide if m > the friction angle



One joint, t=9 ms



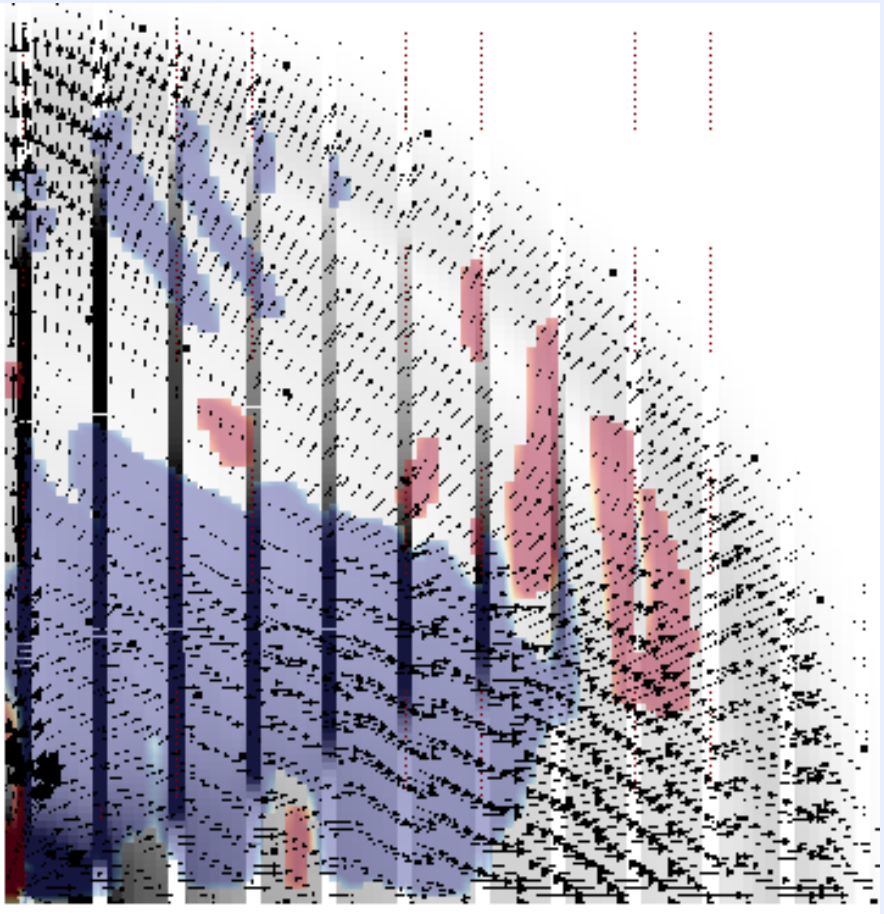
Increasing the number of joints widens the azimuthal region of shear motion



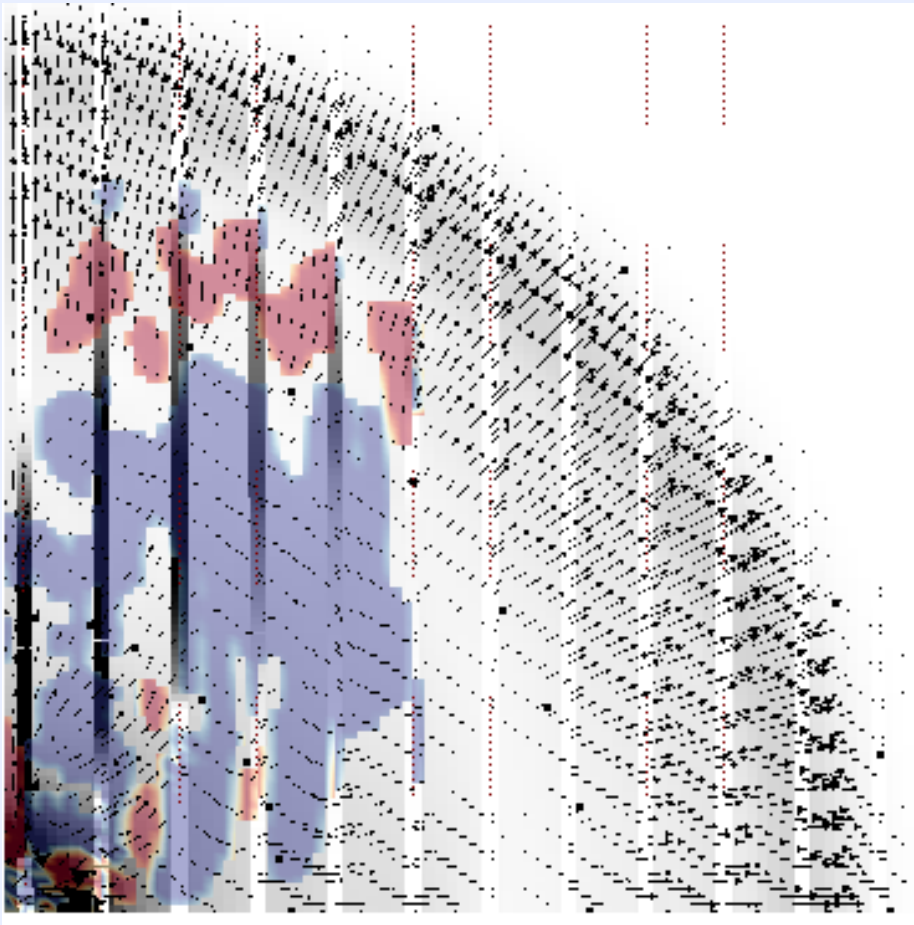
Velocity vectors and tangential velocity directions at 7 ms
Blue clock-wise, red counter-clock-wise.
Friction coefficient=0.6. Slip on the joints is shown in dark grey

The azimuthal region with shear motion also widens with decreasing friction

Friction ~0.4



Friction ~0.8



Anomalous high velocity can be explained by various joint properties in the vicinity of that gauge

Assumptions:

#7-2:

joint spacing= 2.5 m

Friction =0.4

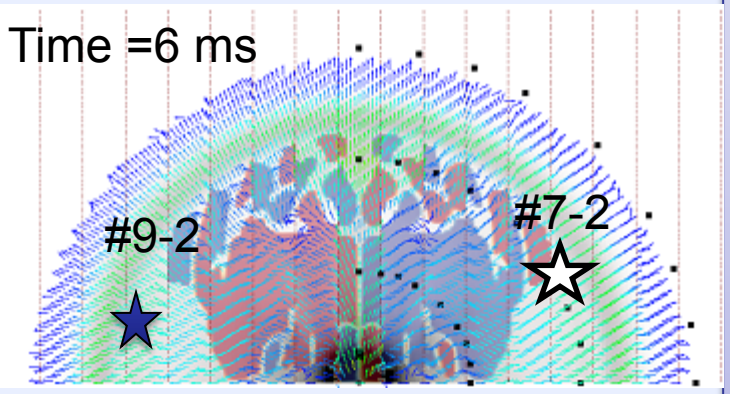
Azimuth =30 degrees

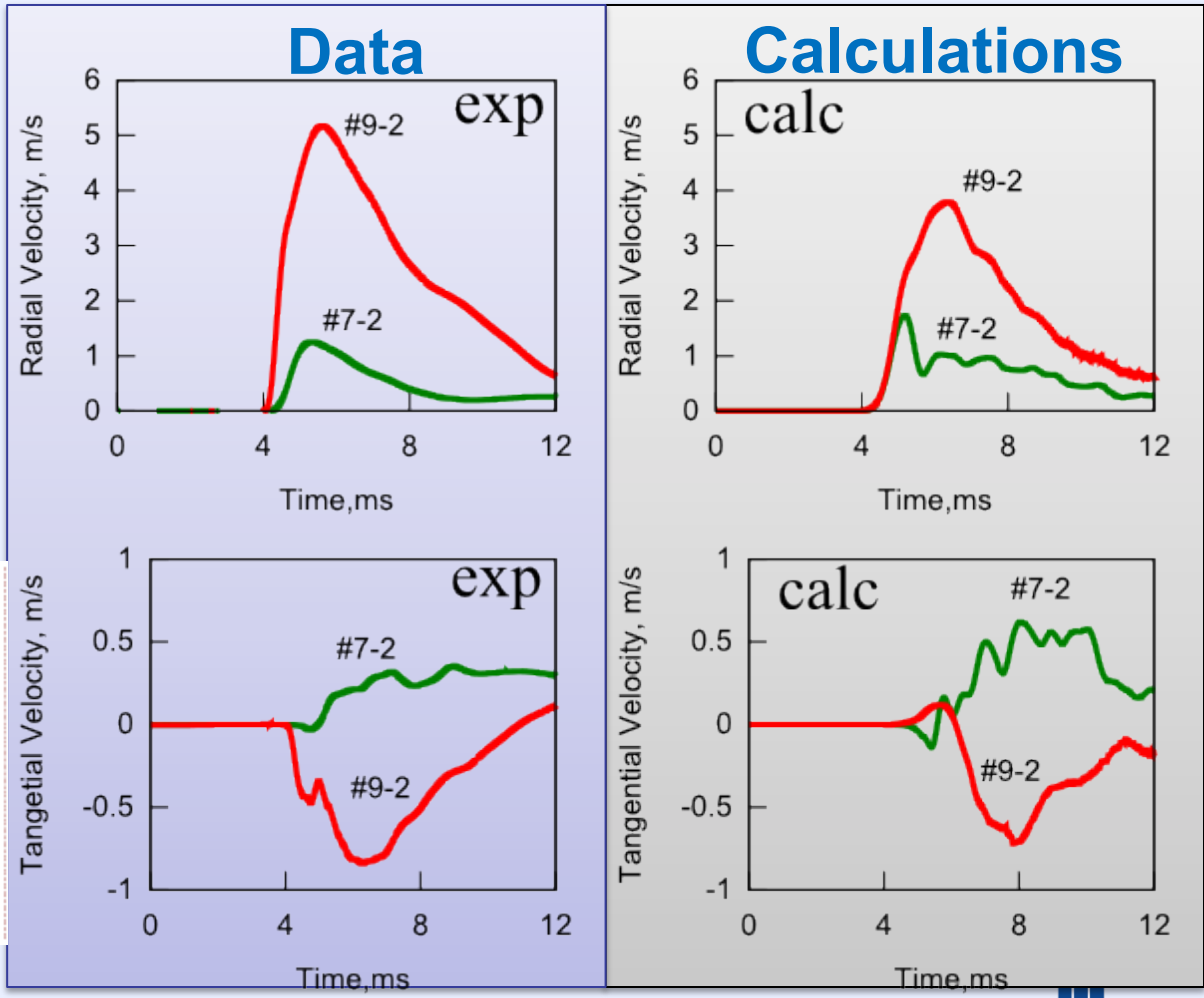
#9-2:

Joint spacing = 1.6 m

Friction =0.2

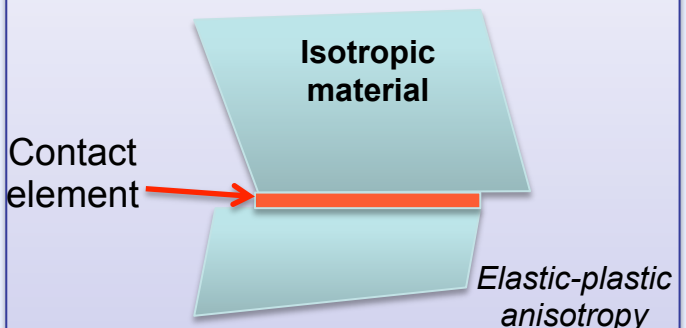
Azimuth= 170 degrees





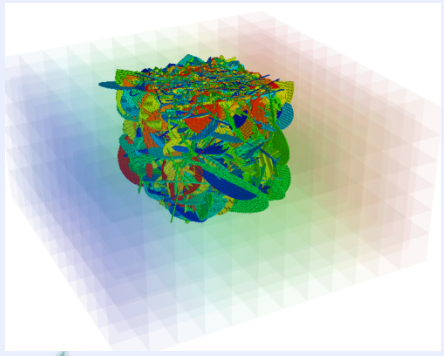
We have employed a continuum joint modeling to study effects of joint orientations and gravity

DISCRETE JOINT



- **Nonlinear normal compliance**
- **Coulomb friction**
- **Valid for large slips and separations**

Bigger domains, more runs



verify

CONTINUUM JOINT

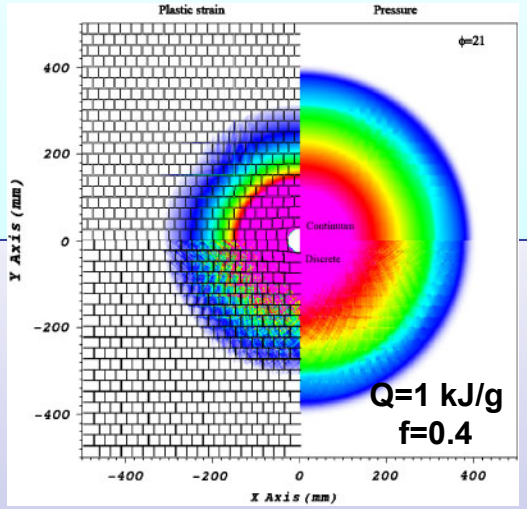
- **No compliance**
- **Coulomb friction**
- **Small deformations**

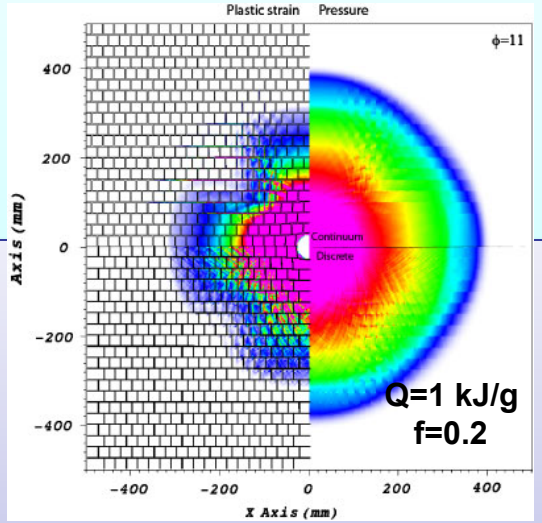
plastic anisotropy

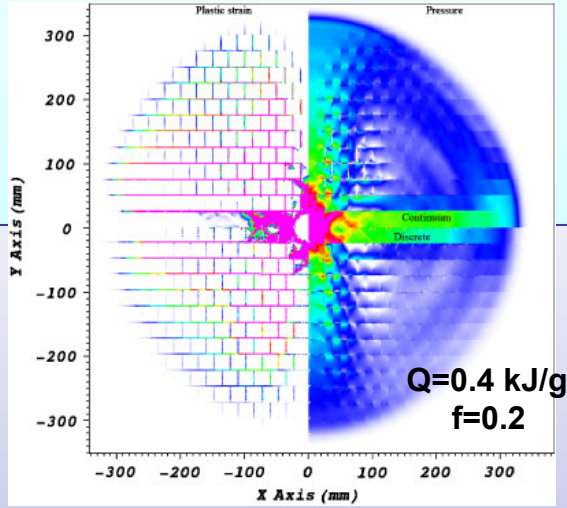
Both discrete and continuum joint models assume that the joint spacing is bigger than the element size

Discrete and continuum joint methods produce similar results where the flow is controlled by plasticity (2D)

CONTINUUM



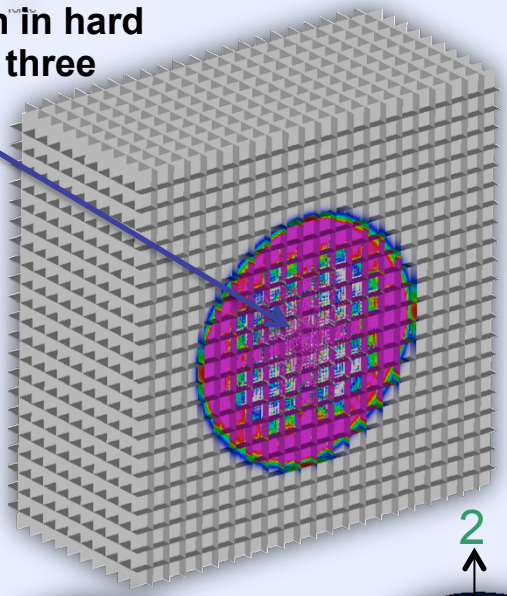


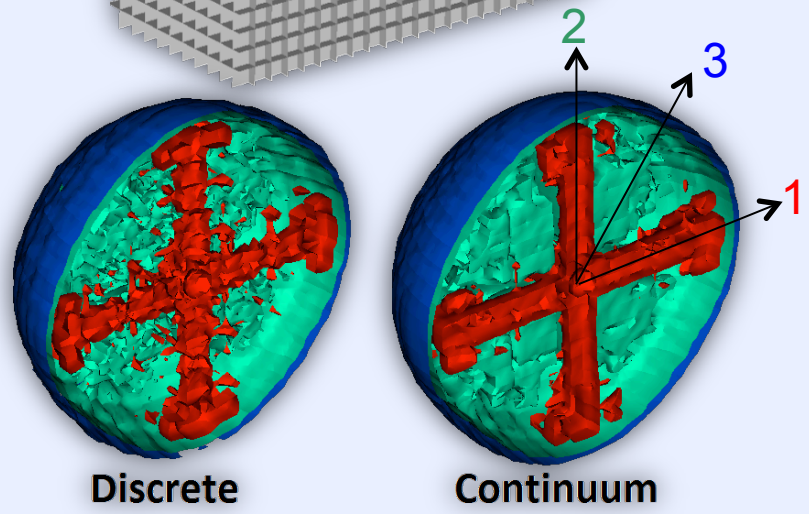


DISCRETE

Discrete and continuum methods show similar results (3D)

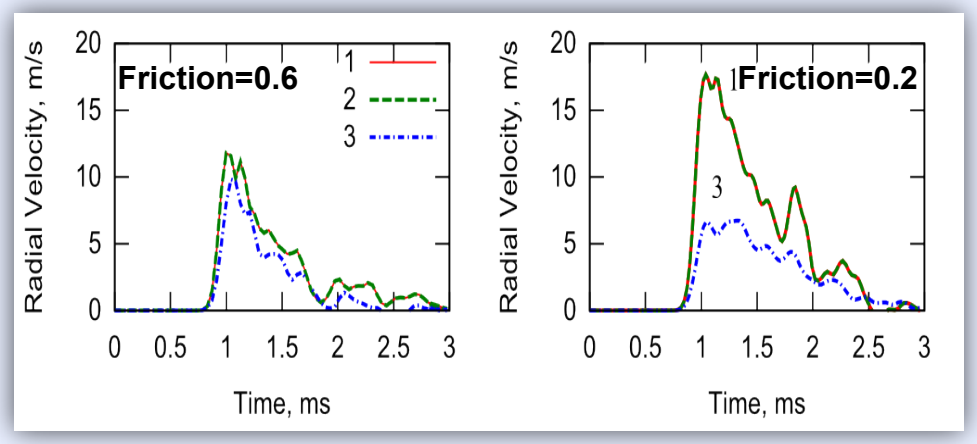
Explosion in hard rock with three Cartesian sets of joints



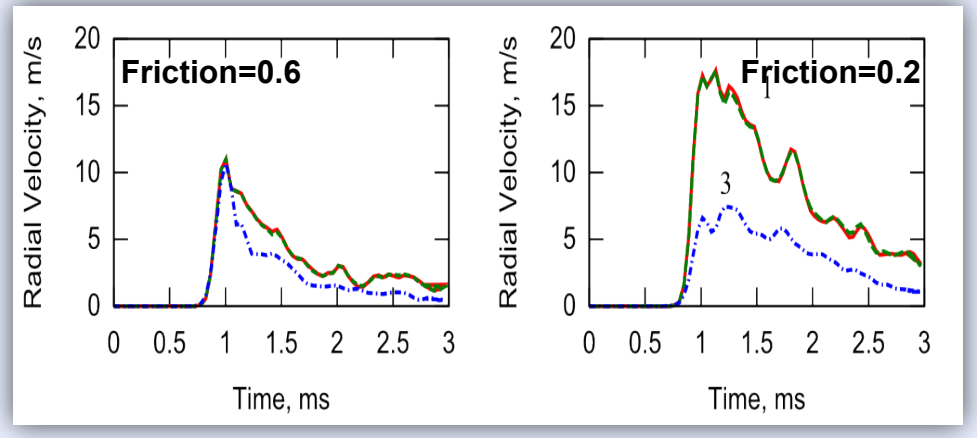


Pressure contours (0-50 MPa)
Joint spacing 1 m, friction ~0.2

Discrete joint representation

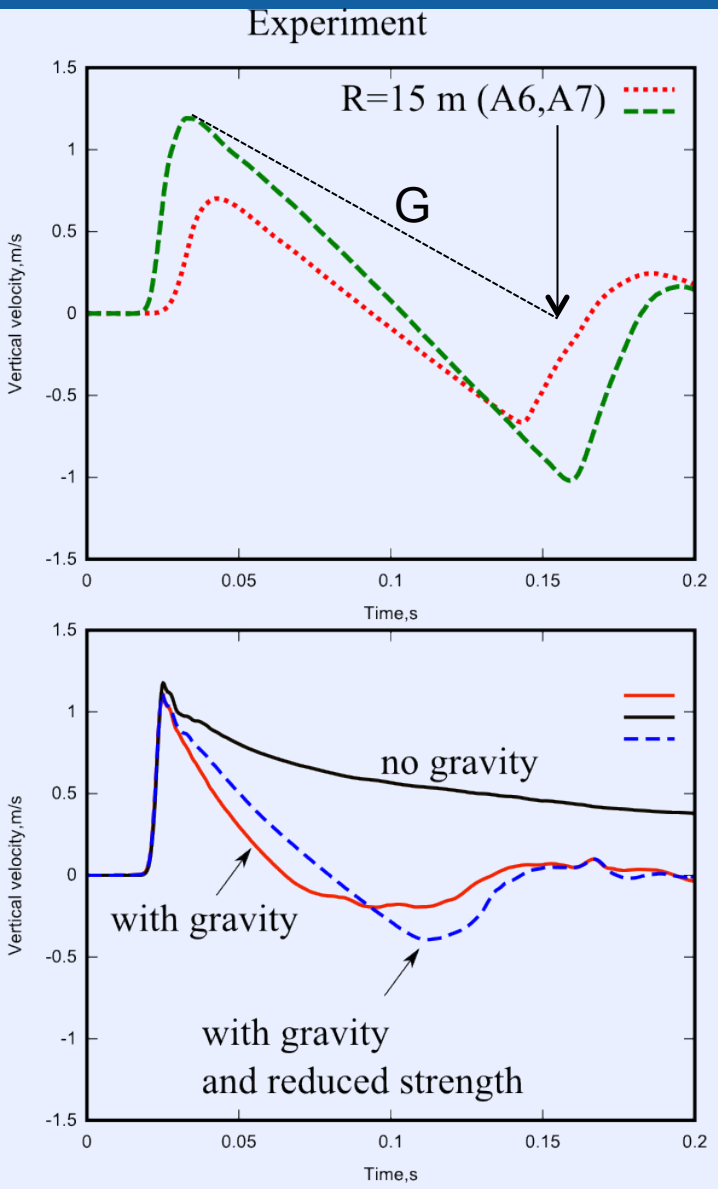


Continuum joint representation

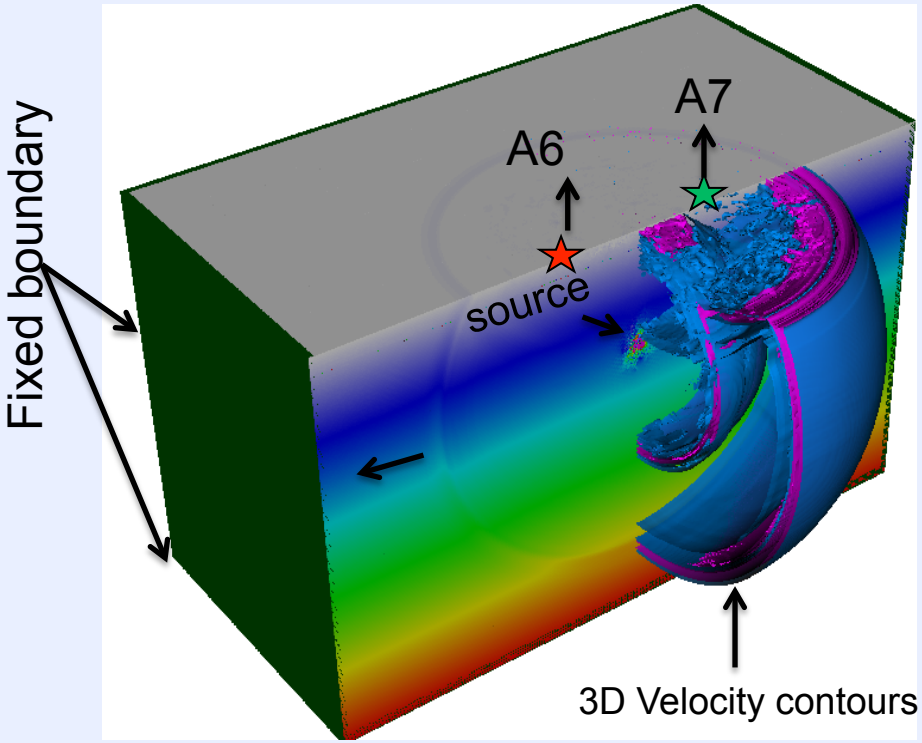


Dependence on joint friction

Material tensile strength affects the vertical velocity calculated at the surface

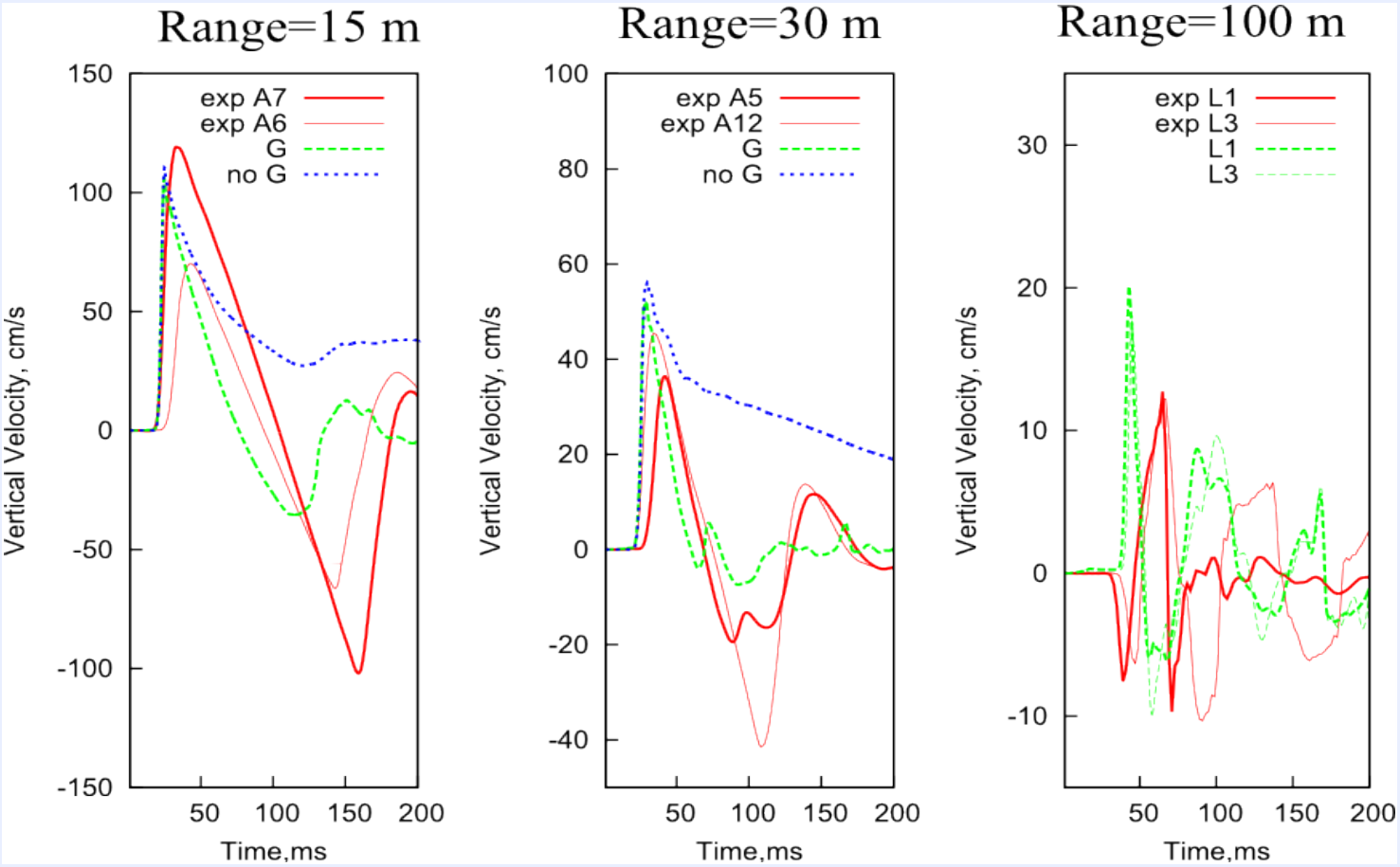


Calculation set up with gravity



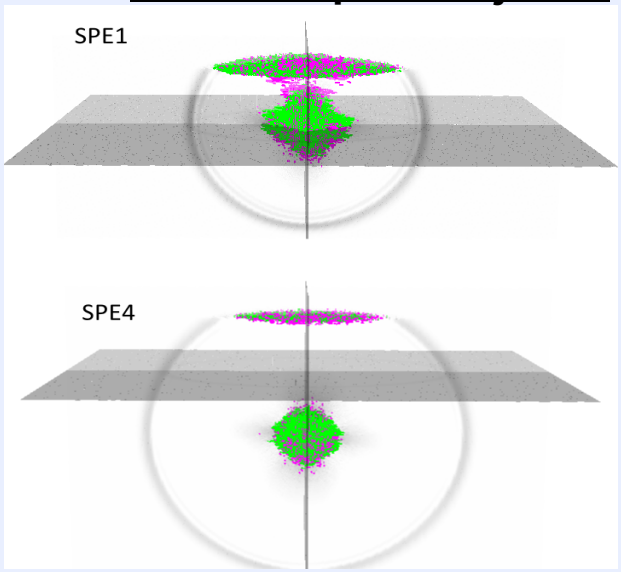
Continuum model with gravity provides reasonable agreement with the surface measurements in SPE3

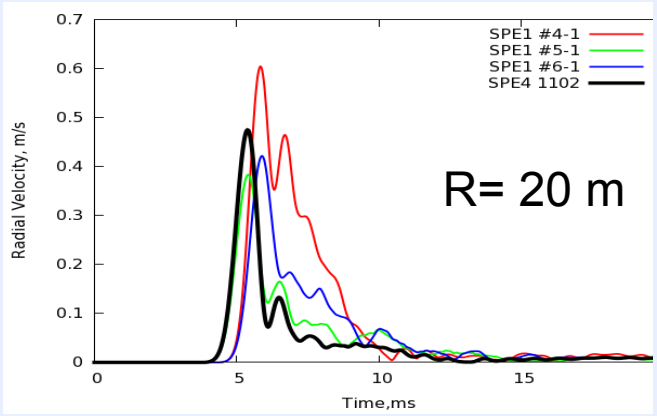
Continuum joint model, 600mx600mx300m domain, 834 CPU, 6 hours



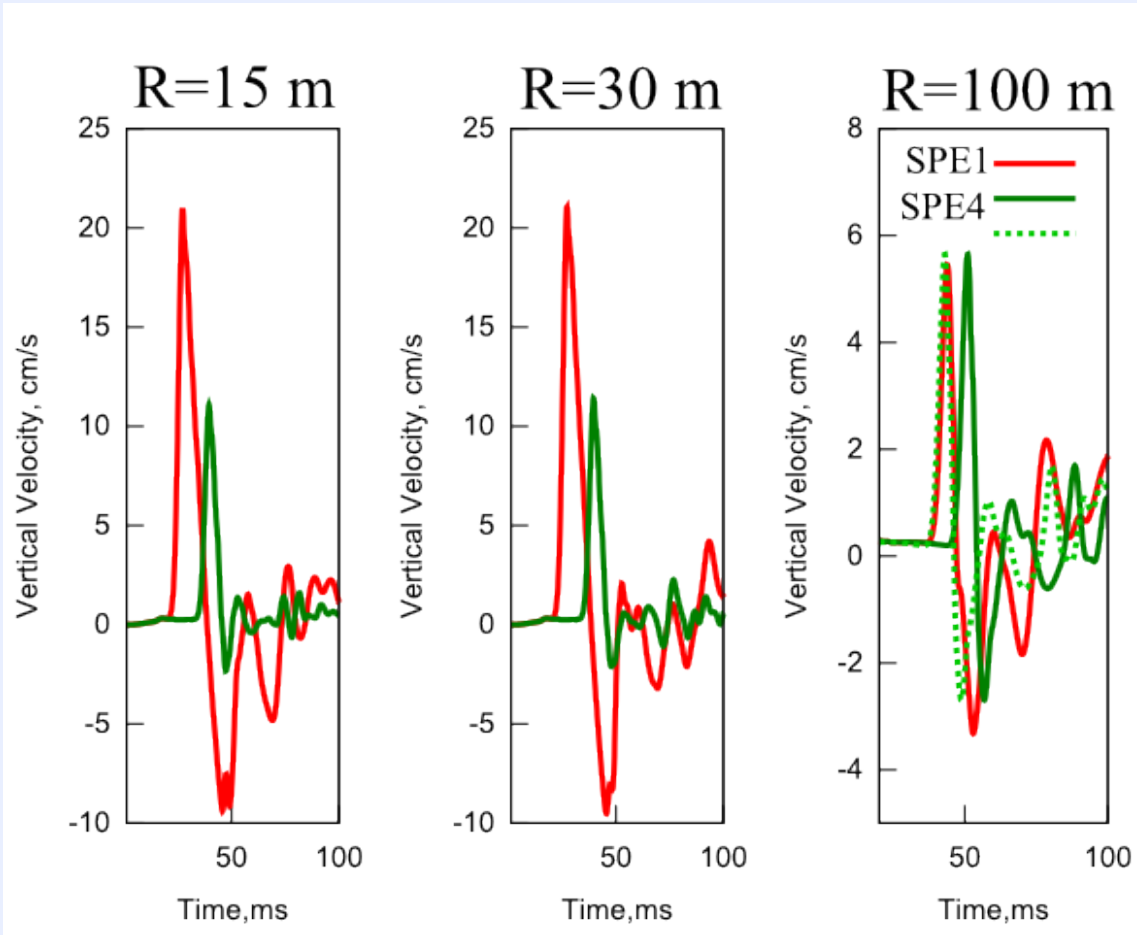
We expect similar near field velocities in SPE4 as in SPE1 with less damage near the surface

Plastic Slip at the joints





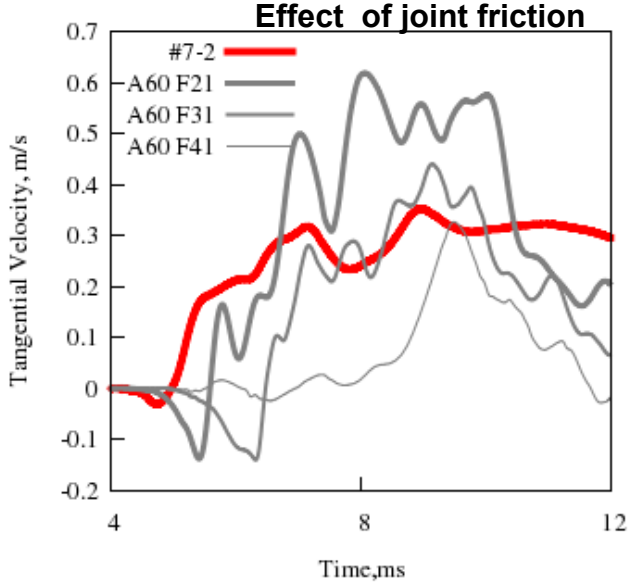
Calculated surface motion (SPE1 vs SPE4) the model is calibrated for SPE3 data first



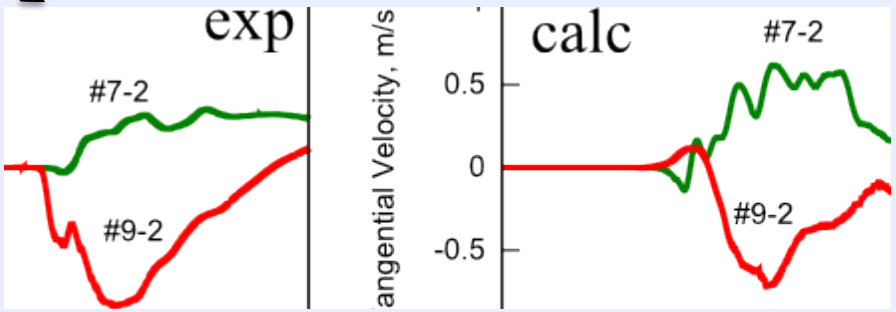
Conclusions

- Vertical Joints can cause significant horizontal motion comparable with that observed in the SPE experiments
- Both joint spacing and friction angle affect the amount of produced shear motion.
- The higher the friction, the shorter and more delayed is the pulse of the shear wave.
- By controlling the joint friction and spacing in a reasonable interval one can describe shear waves that correlate with larger than expected P-wave motion.
- Gravity is important to model the vertical velocity as well as the radial velocity near the surface

Effect of joint friction



Tangential motion cased by one set of joints



For more information:

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Auspices

This work was partially performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Disclaimer

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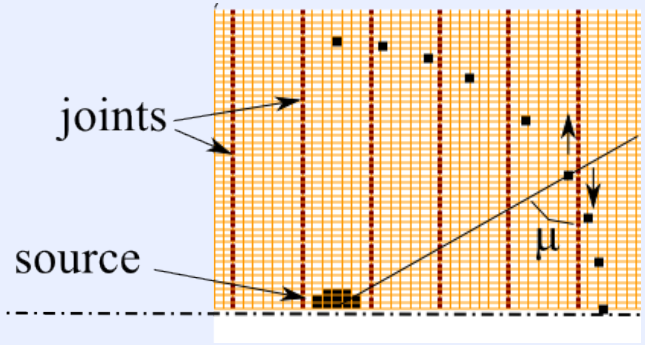
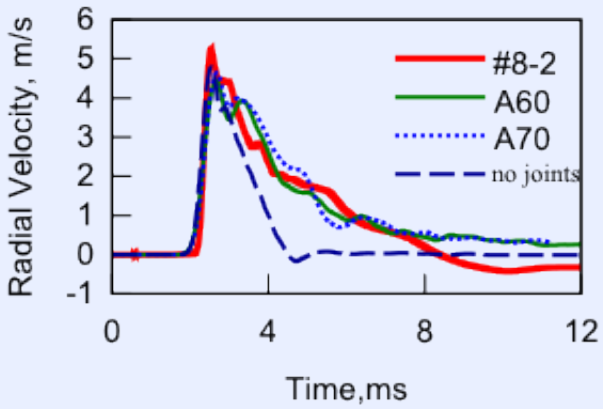
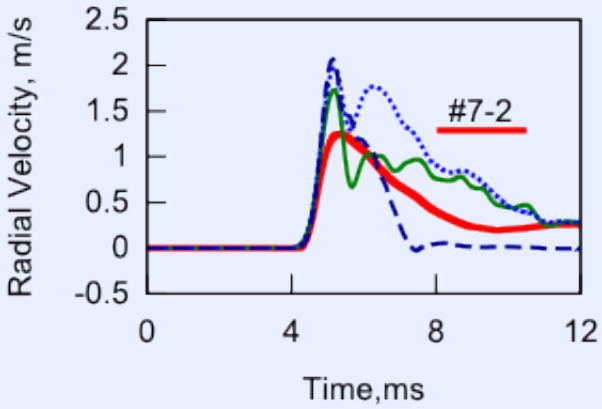
National Laboratory

2D:Transverse and radial motion at 10 and 20 m ranges for 60-70 degree angles

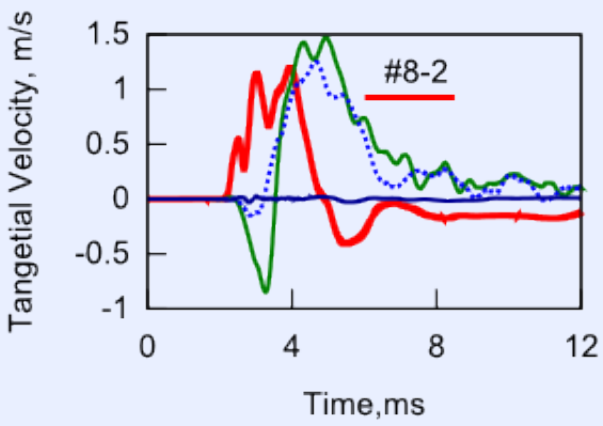


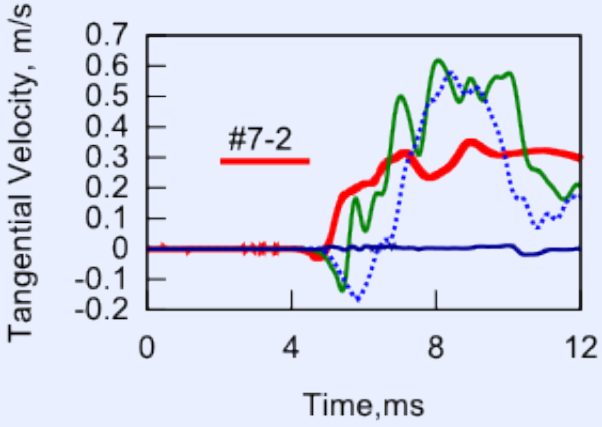
Joint spacing ~2.5 m
Friction angle ~30 deg





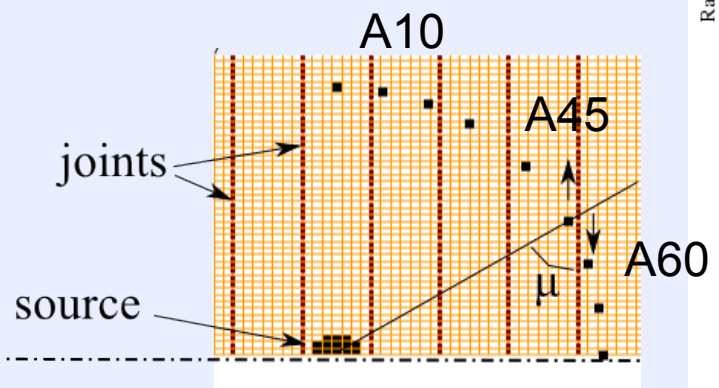
The joints can explain not only tangential motion but also wider radial displacements due to energy redirection (some azimuthal directions will have more and the other ones less energy)

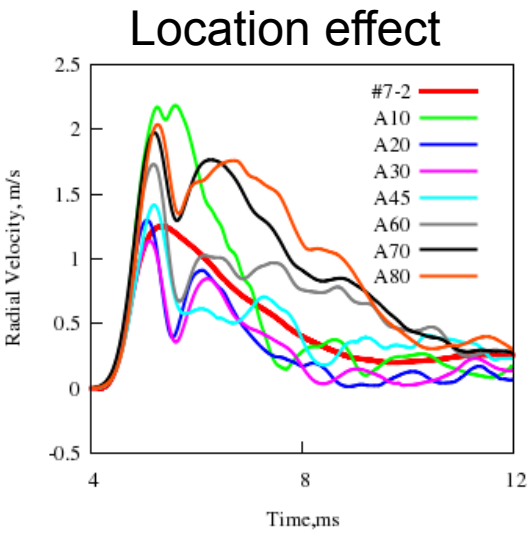


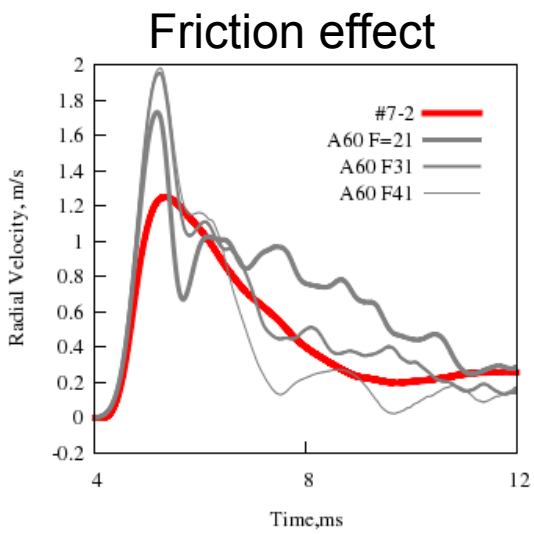


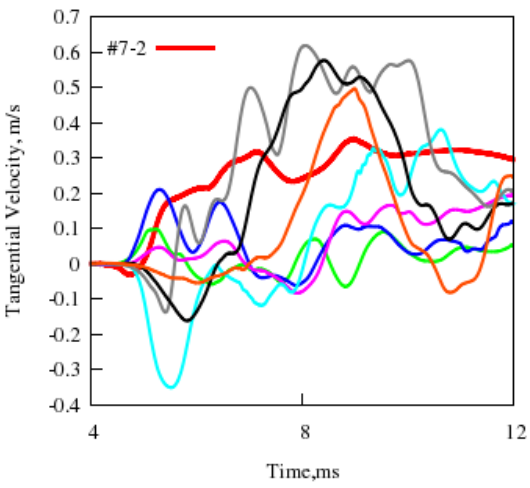
Increasing friction delays the shear motion and makes shear pulse shorter

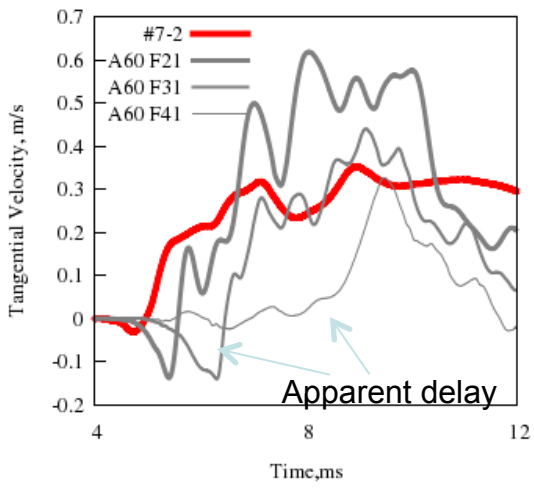
#7-2, R=20 m



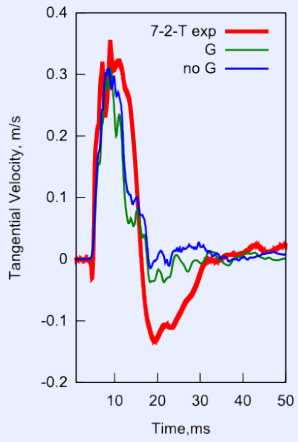


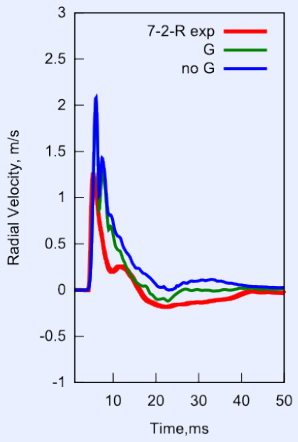


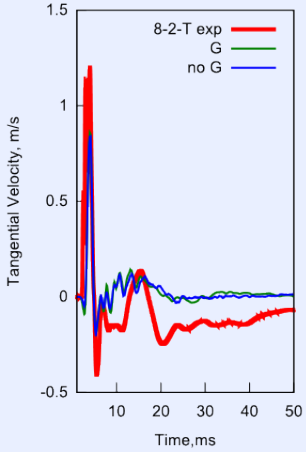


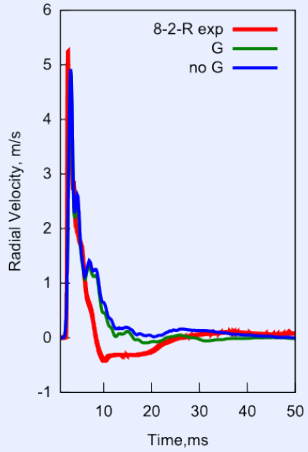


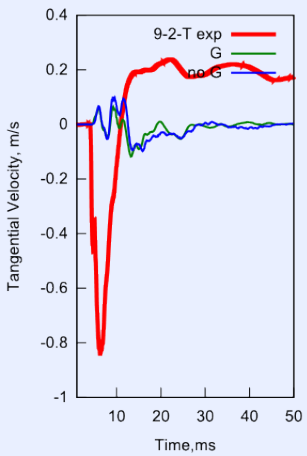
Gravity does not affect velocity histories at R < 20 m

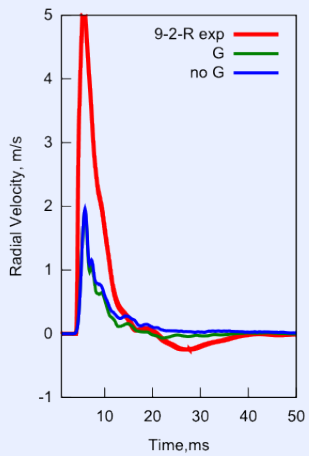


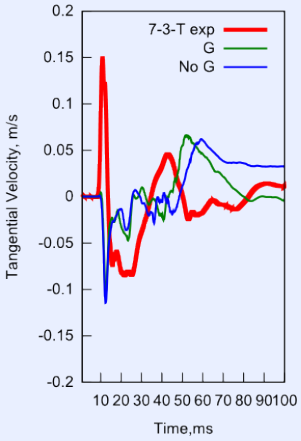


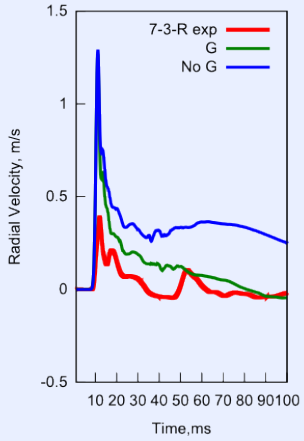


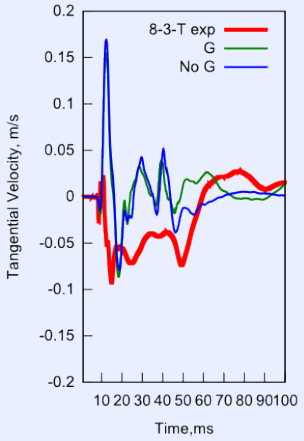


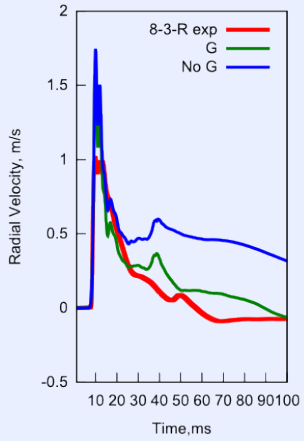


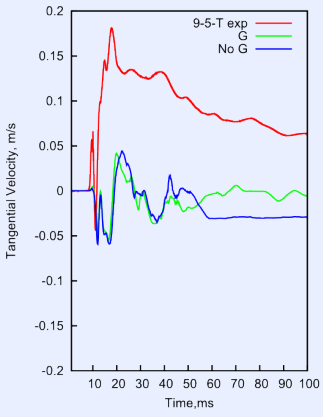


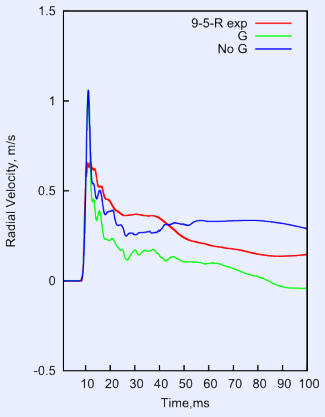




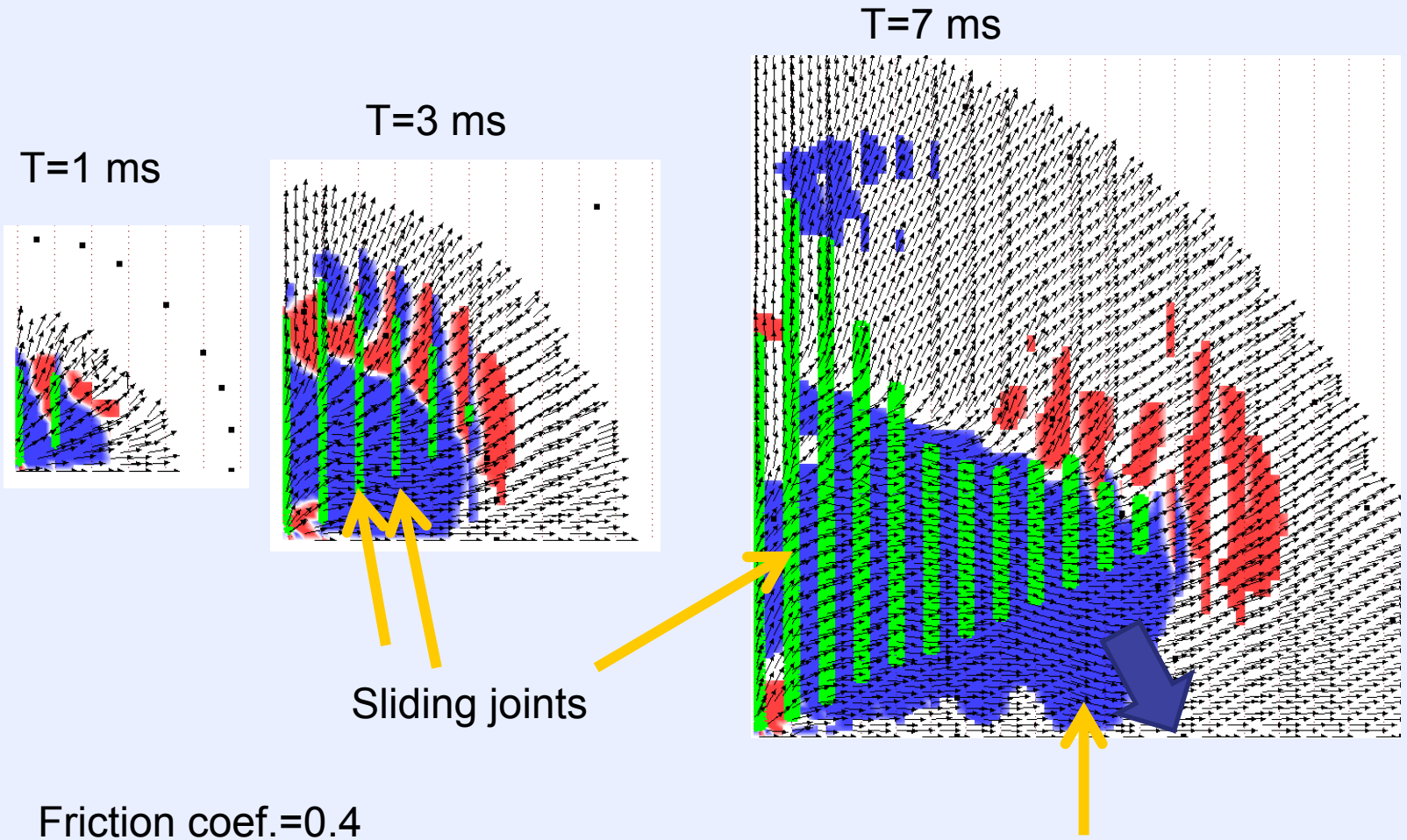






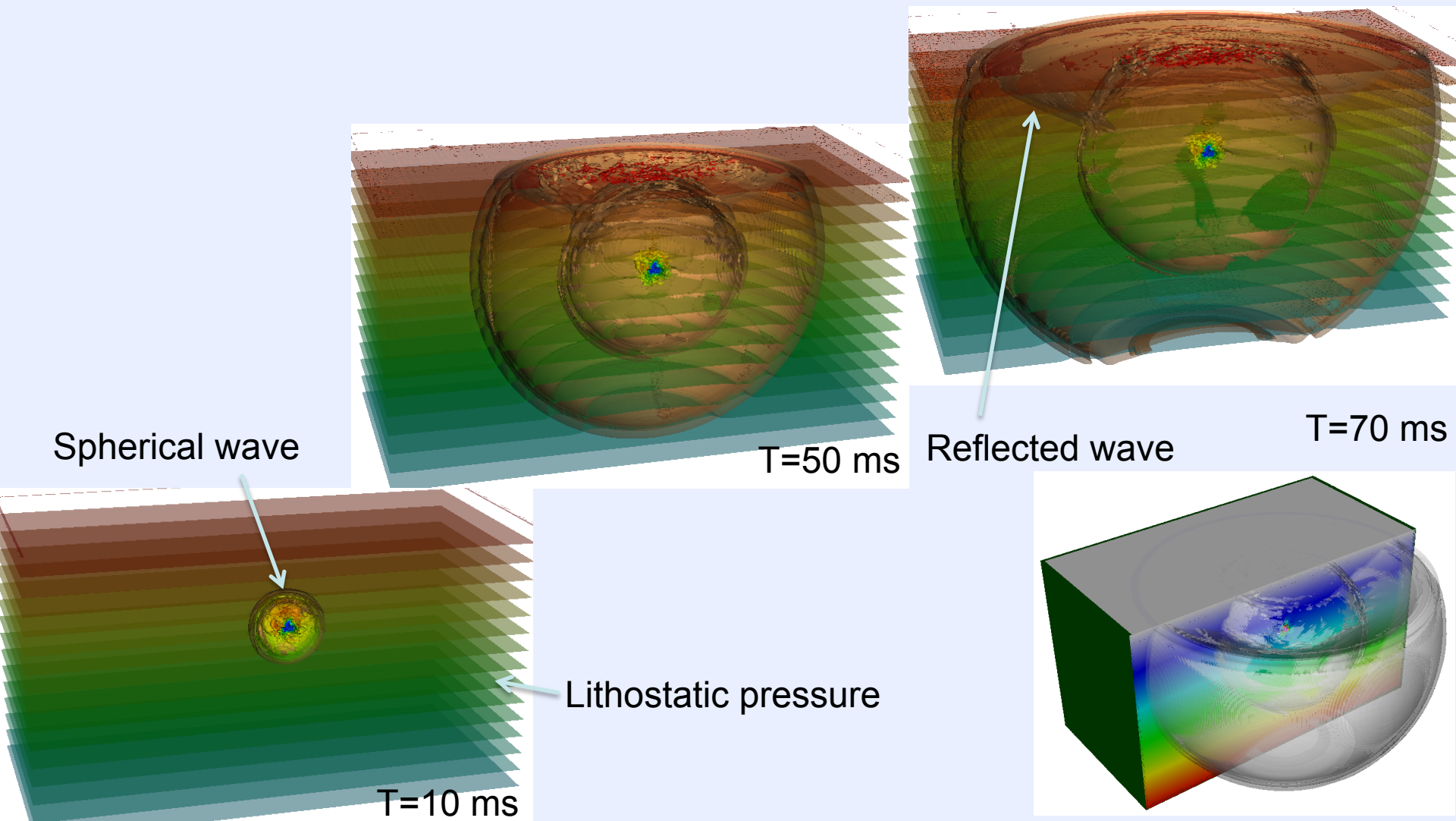


Generation of horizontal shear motion by vertical joints



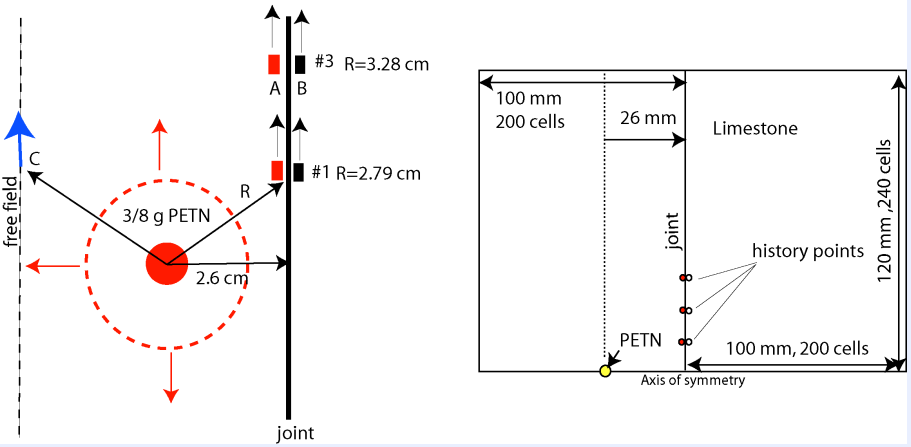
Friction coef.=0.4

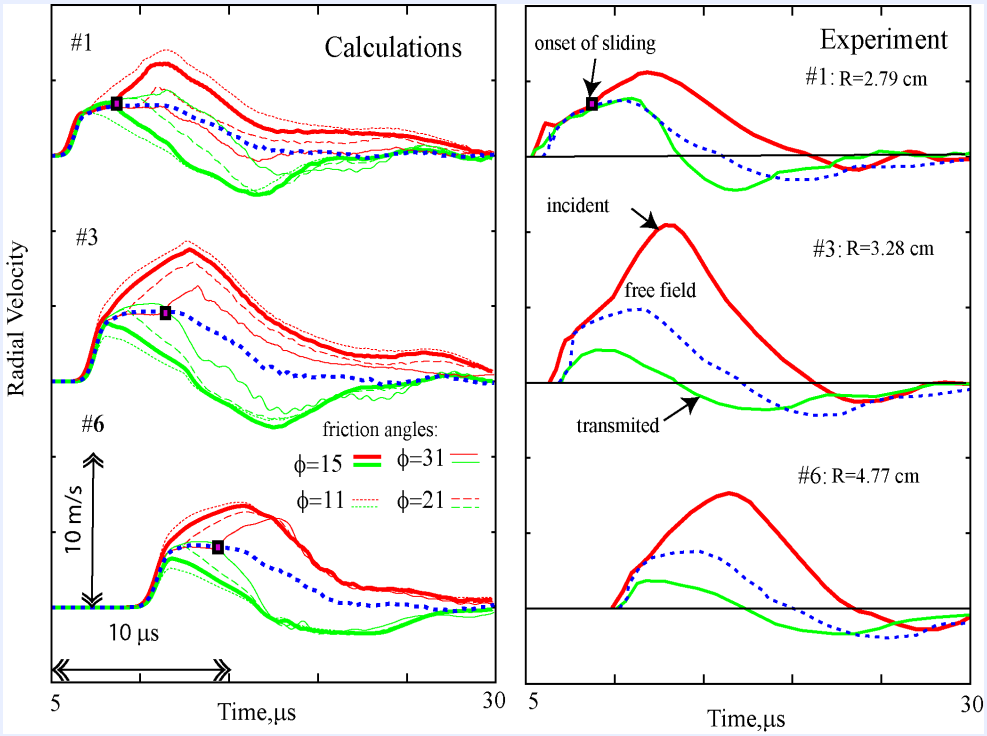
Pressure and velocity iso-surfaces for SPE4 explosion simulation (cross-section)



Joint model has been validated for dynamic conditions

Polished joint in Limestone loaded by a shock wave

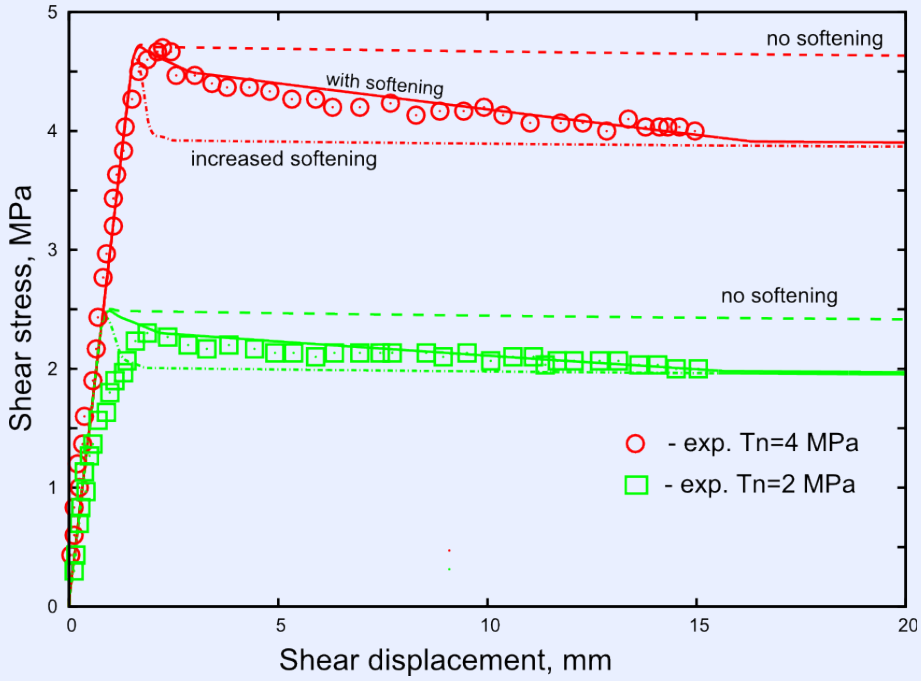




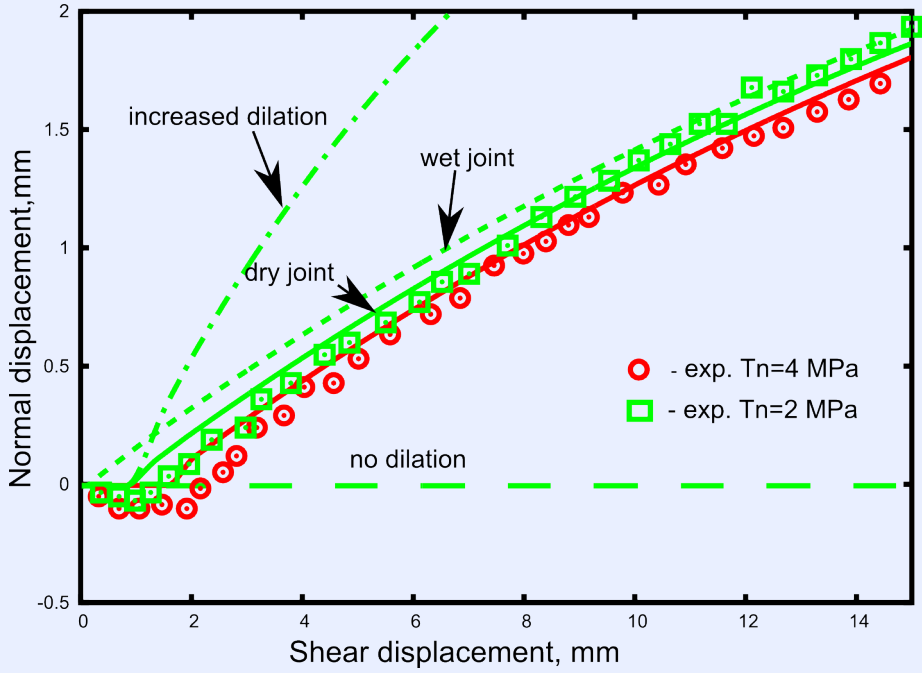
Vorobiev, O.Yu.,(2010),"Discrete and continuum methods for numerical simulations of non-linear wave propagation in discontinuous media", *International Journal for Numerical Methods in Engineering*,83,482-507

Joint model has been validated for quasi-static conditions

Shear test simulation



Joint softening effect



Nonlinear dilatancy